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Shear-Limited Test Particle Diffusion in 2-Dimensional Plasmas

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Abstract.
Measurements of test-particle diffusion in pure ion plasmas show 2D enhancements over the 3D rates, limited by shear in the plasma rotation $\omega_E(r)$. The diffusion is due to "long-range" ion-ion collisions in the quiescent, steady-state Mg^+ plasma. For short plasma length L_p and low shear $S \equiv r\,\partial\omega_E/\partial r$, thermal ions bounce axially many times before shear separates them in θ, so the ions move in (r,θ) as bounce averaged "rods" of charge (i.e. 2D point vortices). Experimentally, we vary the number of bounces over the range $0.2 \leq N_b \leq 10{,}000$. For long plasmas with $N_b \leq 1$, we observe diffusion in quantitative agreement with the 3D theory of long-range $\mathbf{E}\times\mathbf{B}$ drift collisions. For shorter plasmas or lower shear, with $N_b > 1$, we measure diffusion rates enhanced by up to $100\times$. For exceedingly small shear, i.e. $N_b \geq 1000$, we observe diffusion rates consistent with the Taylor-McNamara estimates for a shear-free thermal plasma. Overall, the data shows fair agreement with Dubin's new theory of 2D diffusion in shear, which predicts an enhancement of $D^{2D}/D^{3D} \approx N_b$ up to the Taylor-McNamara limit.

In turbulent fusion plasmas, experiments [1] have observed reduced transport in the presence of sheared flow, but the transport is difficult to calculate theoretically [2]. Here we report measurements of test particle diffusion in a quiescent magnesium ion plasma for direct comparison to a new theory of collisional diffusion in a 2D point-vortex gas with background shear. The ions are kept in steady state with a rotating wall [3] drive superimposed on the confining potential at one end. We observe that for short plasmas (2D) the diffusion rate is up to 100 times larger than for long plasmas (3D). This can be easily understood if we introduce N_b, the number of bounces that a particle makes, in the rotating frame, before being sheared apart (in the θ direction) from a neighboring particle.

We find that N_b controls the 2D transport enhancement over the 3D case. Stated differently, if N_b is large, neighboring particles interact for longer periods of time, leading to more transport. For large N_b the ions can be described as bounce averaged "rods" of charge (which theorists refer to as "2D point vortices"). In the absence of shear, the transport is limited by the Taylor-McNamara paradigm [4], where thermal fluctuations excite large scale, but short lived, convective cells. In the presence of shear, new quantitative theoretical work [5] predicts that the diffusion coefficient is inversely proportional to the shear.

In our experiment, the transport is controlled by the bounce averaged shear, i.e. the average shear that a particle experiences averaged over one bounce along a magnetic field line of the trap. To experimentally determine the $\mathbf{E}\times\mathbf{B}$ shear, we use a laser induced

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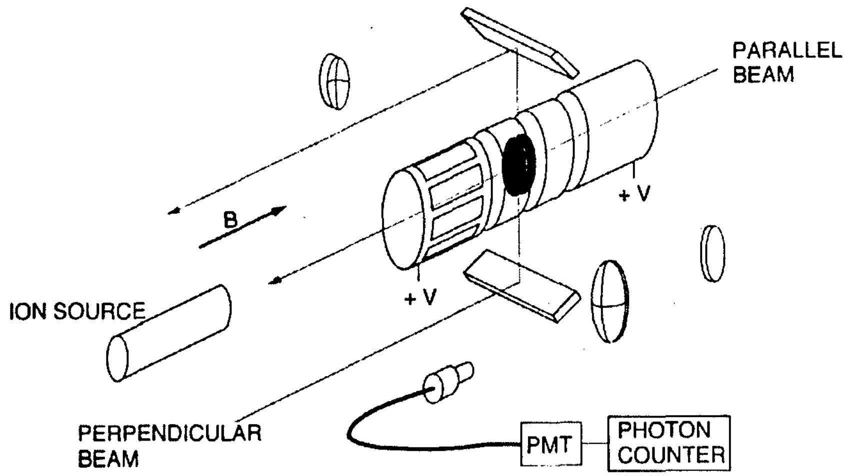

FIGURE 1. Schematic diagram of the cylindrical trap.

fluorescence (LIF) diagnostic, giving the density $n(r)$, the temperature $T(r)$ and the fluid rotation velocity $v_{tot}(r)$ in the $\hat{\theta}$ direction using a perpendicular laser beam as shown in Fig. 1. All the LIF measurements are made in the central plane ($z=0$) of the plasma. For the present work, we have about 10^8 magnesium ions, with a plasma length $L_p \simeq 1$ cm, and a plasma radius $r_p \simeq 2$ cm; the temperature is controlled from 0.1 eV to 4 eV; and the magnetic field is $B = 3$ Tesla. More details about the apparatus and diagnostic can be found in Ref. [6].

The density, temperature and rotation profiles are shown in Fig. 2 for a plasma with small shear (a) and for a plasma with large shear (b). We fit the rotation profile v_{tot} to a smooth third order polynomial. We numerically solve Poisson's equation using the smooth fit to v_{tot} and $T(r)$ with the wall potentials as boundary conditions; and obtain $n(r,z)$ and $\phi(r,z)$. From this solution, one obtains the shear rate $S(r,z) = r d\omega_E(r,z)/dr$ and the bounce averaged dimensionless shear rate [5]

$$\langle s(r) \rangle_z = \left\langle \frac{S(r,z)}{2\pi\, n(r,z)\, ce/B} \right\rangle_z .$$

The dimensionless shear rate $s(r)$ represents, for the case of a "top hat" profile, the shear rate divided by the local rotation rate. Figure 2 also shows $\langle s \rangle_z$; the squares represent the bounce average shear, the solid line a simple estimate of $s(r, z=0)$ directly from $v_E(r) = v_{tot}(r) - v_{dia}(r)$ where the diamagnetic drift is calculated from the measured $n(r)$ and $T(r)$. In the case of Fig. 2(a) which has a very small shear for small radius, $\langle s(r) \rangle_z \simeq s(r, z=0)$ for $r < 1$ cm.

The electronic spin orientation of the ground state of Mg^+ is used to "tag" the test particles. The flux of test particles Γ_t is obtained from the measured test particle density n_t as

$$\Gamma_t(r,t) = -\frac{1}{r}\int_0^r dx\, x \frac{\partial}{\partial t} n_t(x,t) + \int_0^r dx\, x \frac{2n_t(x,t) - n(x)}{\tau_s(x)} ;$$

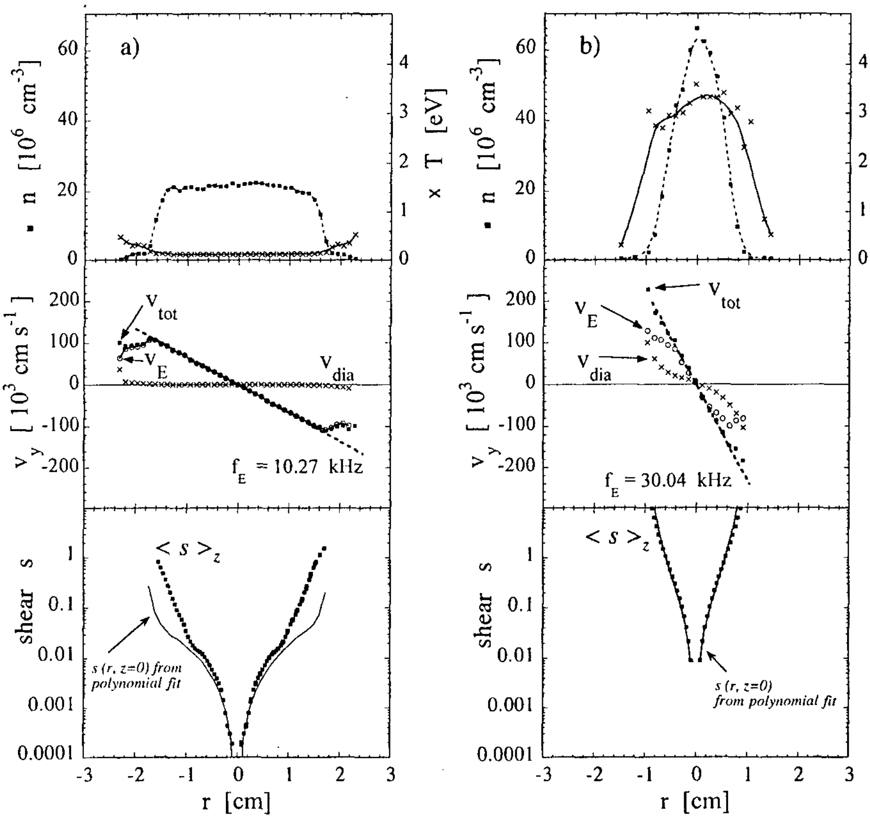

FIGURE 2. Profiles of density n, temperature T, velocity v, and dimensionless shear s. (a) Small shear case; (b) large shear case.

the second term corrects for the weak spontaneous spin flip at a measured rate τ_s^{-1}. We verify that the flux of test particles is proportional to the gradient of the concentration of test particles, i.e.

$$\Gamma_t(r,t) = -D(r)n(r)\frac{\partial}{\partial r}\left(\frac{n_t(r,t)}{n(r)}\right)$$

and obtain the local diffusion coefficient $D(r)$.

Figure 3 shows preliminary measurement of the diffusion coefficient normalized to the plasma length L_p and magnetic field B as a function of the dimensionless bounce-averaged shear $\langle s\rangle_z$. For $\langle s\rangle_z \gtrsim 0.1$ the measured diffusion coefficient agrees quantitatively wilth the 3D diffusion coefficient previously measured in long plasmas [7]; here, D^{3D} is calculated with values of n and T appropriate to the high-shear data points. As the shear decreases, the diffusion coefficient increases roughly proportional to s. For

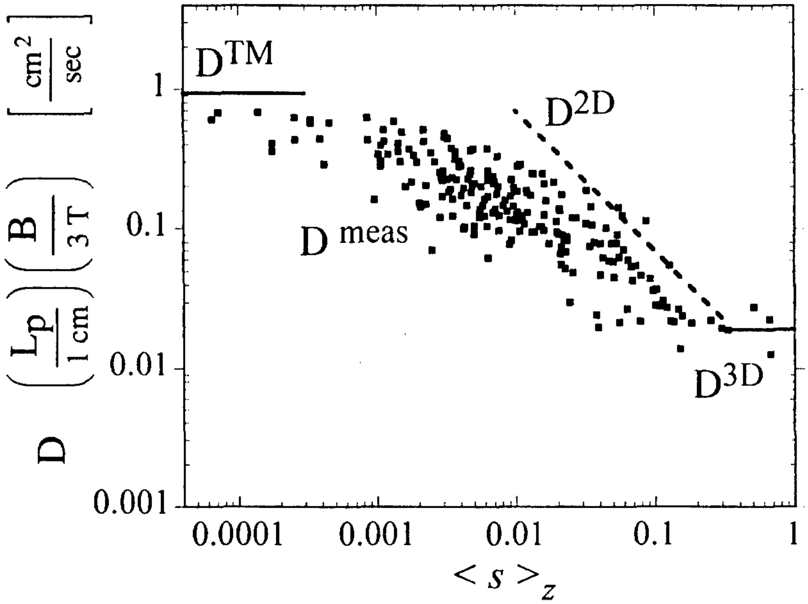

FIGURE 3. Diffusion coefficient normalized to plasma length L_p and magnetic field B versus the dimensionless bounce average shear.

$\langle s \rangle_z \leq 5 \times 10^{-3}$ the diffusion coefficient approaches a limit within a factor of two of the Taylor-McNamara shear-free theory. Here, D^{TM} is calculated from the number of particles N in the low-shear plasmas.

Recent theoretical work has investigated diffusion processes in the presence of shear for a collection of 2D point vortices [5]. Overall, the data shows fair agreement with the present theory, but proper consideration of the end shape and Debye shielding of the fluctuations will have to be included. To summarize the theories, we have the 3D long range collisional diffusion [8]:

$$D^{3\mathrm{D}} = 2\alpha\sqrt{\pi}\, n\bar{v}b^2\, r_c^2 \ln(\bar{v}/\Delta v_{\min})\ln(\lambda_D/r_c) \propto B^{-2}nT^{1/2},$$

where $\alpha = 3$ represents the multiple effective collisions due to "velocity caging." This is in quantitative agreement with the experiments [7] in long plasmas (i.e. $N_b \leq 1$). Here $b \equiv e^2/T$ is the classical distance of closest approach, and the minimum relative velocity for these collisions is $\Delta v_{\min} \approx (n\bar{v}^3 b^2 \sqrt{r_c \lambda_D})^{1/3}$.

The 2D shear-limited diffusion [5] is

$$D^{2\mathrm{D}} = \frac{1}{2\langle s \rangle_z}\left(\frac{e}{L_p}\frac{4\pi c}{B}\right)\ln\left(\frac{r}{d}\right) \propto B^{-1}\langle s \rangle_z^{-1} L_p^{-1},$$

where $d \equiv (4D^{2\mathrm{D}}/|S|)^{1/2}$ is the (diffusion-limited) minimum impact parameter for these collisions. In the limit of zero shear, Taylor and McNamara calculated [4] a diffusion

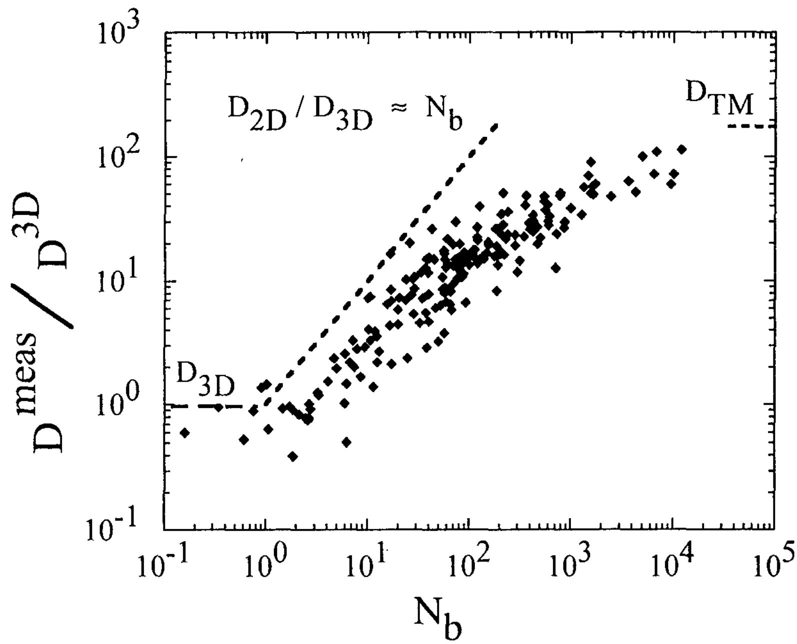

FIGURE 4. The diffusion coefficient normalized by the 3D long range $\mathbf{E} \times \mathbf{B}$ drift collision case increases with N_b.

(neglecting considerations of Debye shielding) of

$$D^{\mathrm{TM}} = \frac{ce}{2\pi^{1/2}} \frac{\sqrt{N}}{B\, L_p} \propto B^{-1} N^{1/2} L_p^{-1}.$$

These theories scale differently with all plasma parameters. However the enhancement ratio $D^{2\mathrm{D}}/D^{3\mathrm{D}}$ depends only on the number of bounces a particle makes in the rotating frame before being sheared apart, given by

$$N_b \equiv \frac{f_b}{r\omega_E'} = \frac{\bar{v}}{2L_p r\omega_E'}.$$

Figure 4 shows the measured diffusion coefficient normalized to $D^{3\mathrm{D}}$. The solid line is the theory prediction at $B = 3$ T for $D^{2\mathrm{D}}/D^{3\mathrm{D}} \approx N_b$. One can see that the diffusion increases as particles interact for longer periods, i.e. for large N_b. For $N_b \leq 2$ the diffusion is correctly described by 3D long-range collisions; in contrast for $N_b \gtrsim 5000$ the diffusion approaches the Taylor-McNamara limit. For $1 < N_b < 100$, the predicted $D^{2\mathrm{D}}/D^{3\mathrm{D}}$ is in fair agreement with the experiments, being generally about $3\times$ larger than observed. Further theory and experiments may elucidate the effects of the end confinement fields and the effects of Debye shielding.

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